WATER MOVEMENT DEDUCED FROM TEMPERATURE VARIATIONS IN LAKE BIWA-KO

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WATER MOVEMENTS DEDUCED FROM TEMPERATURE VARIATIONS IN LAKE BIWA-KO[1]

By

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Abstract

The simultaneous observation of water temperature has been hourly made during 25 hours on the two anchored vessels in Lake Biwa-ko, Honshu, Japan. The water temperature variations with time are as follows : these involve periodic oscillations at both stations ; and except in the homogeneous upper layer, temperature of any subsurface waters gradually descends at both stations, while it is almost always higher at one station than at the other. The transverse internal seiche is found to exist with the period of 9 hours. The convective movements of water which may be caused by the wind action in the layers above and below the thermocline are discussed by the use of the calculation of the geopotential height of isobaric surfaces based on the water temperature.

1. Introduction

There have been not a few studies of internal seiche in some lakes (Hutchinson [1957]). Mortimer [1952] pointed out that the internal seiche was an important factor in lake environment, and made a comprehensive observation in Windermere with model investigation.

The internal seiche or internal wave is indeed a significant phenomenon in stratified lakes. Influence of internal seiches on the distribution of plankton, fish, etc. may sometimes be considerable, because the horizontal or vertical movement of surrounding waters attains to a large distance. As the water currents related to the internal seiche have often large velocity gradients, it is important to the process of water mixing. In Lake Biwa-ko, the water current in hypolimnion seems to be small as compared with in epilimnion as far as direct measurements by the present author are concerned (unpublished), and the movement in hypolimnion may be mainly attributed to the internal seiche. The internal seiche also causes a periodic variation in the distribution of the water density. Though the water circulation of Lake Biwa-ko can be dealt

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with as a geostrophic flow (Okamoto and Morikawa [1961a, 1961b]), it has recently become clear through the repeated soundings that the horizontal and vertical distribution of water temperature, upon which a calculation of geopotential height must be founded, takes frequently some distorsion or fluctuation.

There are few observations of the water movement in subsurface layer (Hutchinson [1957]). Analyzing the current meter records in Lake Michigan, Verber [1964] suggested that the wind effect was transmitted to the deepest portions of that lake in a few hours. The free oscillation of Lake Erie has been found to be influenced by the earth's rotation (Platzman and Rao [1964]).

In Lake Biwa-ko, the temperature sounding at an anchored station has suggested the existence of internal seiche (Morikawa and Okamoto [1963]). In order to ascertain its existence, to research its characteristics and to estimate its influence on the geopotential height, a series of temperature observation has been simultaneously conducted at two stations. This paper presents a time variation of temperature observed at both stations, from which the water movement has been deduced.

2. Observations of water temperature

Hourly observations of water temperature were carried out for 25 hours from 13 h on 29 th to 14 h on 30 th July in 1965 at two anchored stations, which were occupied by the *Kosei* (Shiga University) and the *Nio* (Ministry of Construction) respectively. One of them was off Myozinzaki and the other off Okinoshima Island as shown in Fig. 1. Water depth of the former (Station 1) was 53 meters and the latter (Station 2) 51 meters. The temperature was read at every 2 m depth in the water layer between the surface and 20 m depth, and at every 5 m below that layer to the bottom. The apparatus for measurement was portable thermistor thermometer at both stations, and an automatic recorder of the temperature was also set at Station 1. The automatic recorder has sometimes caught at a few depths a oscillatory change of short period (2–5 minutes) ranging 0.5°C, which will be reported in detail in other paper. The measurement error did not usually exceed 0.2°C, al-

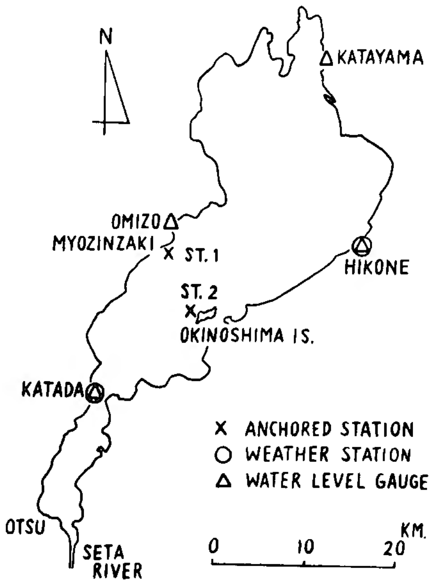

Fig. 1. Location of the stations.

though it attained occasionally to 0.4°C in particular in the thermocline on account of declining of leading electric cord at the time of fairly strong wind.

It is apparently seen from the temperature profile that a well developed thermocline lies between 9 m and 18 m depth. Above and below the thermocline the temperature varies slightly. Such as this vertical distribution of temperature is not particular but is at all times found in this season (Morikawa and Okamoto [1963]). Some examples of temperature variation observed at both stations are illustrated in Fig. 2.

3. Transverse internal seiche

Time variations of temperature as shown in Fig. 2 are complicated at first sight, but are noticed to have such characteristics as follows : (1) The temperature in the thermocline indicates a large fluctuation which involves periodic

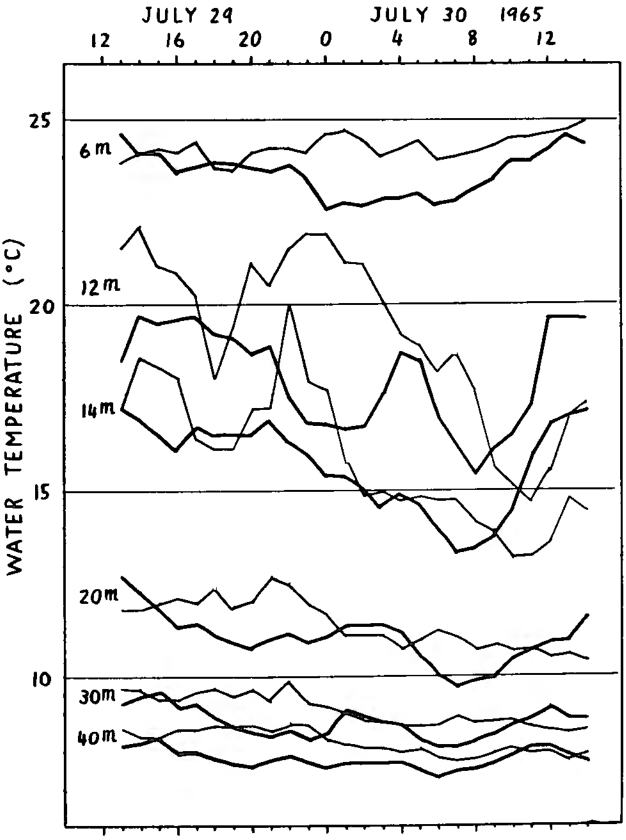

Fig. 2. Some examples for time variation of the water temperature in the surface layer (6 m), thermocline (12 and 14 m), and deep layer (20, 30 and 40 m) at the two anchored stations. Thick line: Station 1. Thin line : Station 2.

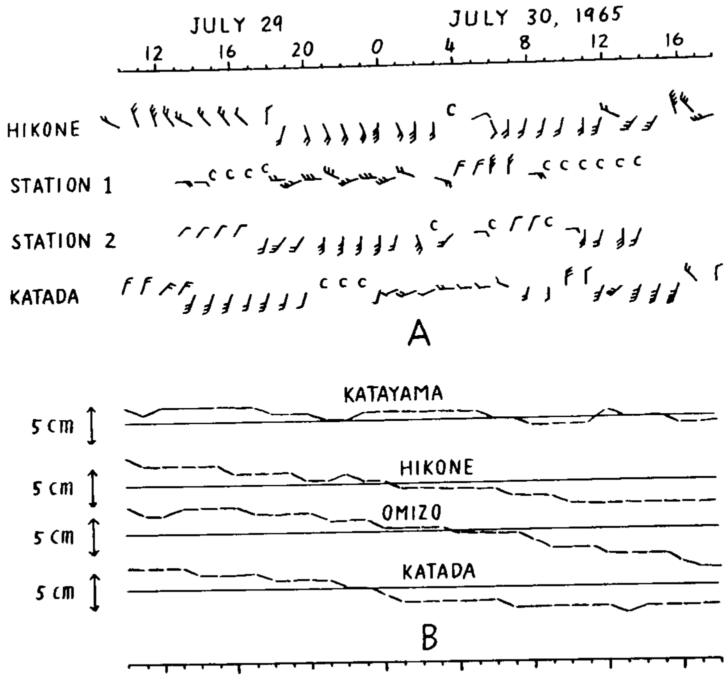

Fig. 3. Time variations of wind (A) and of water level (B) at the stations as shown in Fig. 1. The letter "C" means calm.

oscillation that seems to be "out of phase" at each other station. (2) At both stations the temperature has a trend to descend till morning on 30 th and afterwards turns to ascend. (3) During the stage for descent it is warmer at Station 2 than at Station 1, and on the contrary during the stage of ascent it is warmer at Station 1 than at Station 2, except for surface layer.

At the first place description about (1) will be given. Remembering that both stations lie on a transverse section, "out of phase" might suggest the transverse internal seiche. Now, if the assumption that the lake water consists of two homogeneous waters which are divided with the thermocline is made, one can calculate the period T of uninodal seiche by the equation,

$$T=2l\left\{\frac{1}{g}\frac{\rho'}{\rho'-\rho}\left(\frac{1}{h}+\frac{1}{h'}\right)\right\}^{1/2},$$

where l is transverse length, g is acceleration due to gravity, ρ and ρ' are water density of the upper and lower layer, h and h' are thickness of the upper and lower layer. Taking that $l=9$ km, $g=980$ cm/sec^2, $\rho'-\rho=2.5\times10^{-3}$ gm/cm^3, $\rho'=1.00$ gm/cm^3, $h=14$ m, and $h'=36$ m (average depth of the basin is 50 meters), T is computed at 10.2 hours. On the other hand observed period is perceived to be 9 hours. This discrepancy depends perhaps upon the above assumption of the two layers.

At the next place we estimate the magnitudes of the velocity due to the transverse internal seiche. Mean amplitude of temperature oscillation in the thermocline is 1.4°C, while the vertical gradient is averaged at 1.2°C/m. Therefore the amplitude of the oscillation of the thermocline is 1.2 m, and accordingly the amplitude of transverse current at a node is estimated 3.8 cm/sec in the upper layer and 1.4 cm/sec in the lower layer.

4. Longitudinal movement

In this section the time variations of temperature, items (2) and (3) described in the preceding section, will be interpreted. The descending trend recognized in all layers except in the upper homogeneous layer tells us that the warm water has been gradually displaced by the cold water. Such displacement, however, does not seem to occur directly owing to the horizontal advection of the water mass which has another vertical distribution of temperature, because a temperature descent has taken place at the same time at both stations. Descending trend might be counted for the upwelling. Where has the warmer water gone?

On the other hand the wind observation has hourly been performed at both anchored stations. Fig. 3 A shows the wind at anchored stations in Beaufort scale together with hourly readings at the two weather stations, Hikone and Katada, whose locality is shown in Fig. 1. Over these four stations the wind is not always uniform but varies from place to place, and in particular the winds at Station 1 do not seem to be representative because of its locality near by the mountains. From 18 h on 29 th (from 14 h at Katada) to 4 h on 30 th (to 0 h at Katada), southerly wind blew consistently, which must have caused the northward water current of the surface layer. When the water is in motion Coriolis force continues to act uppon the water into the right deflection in the northern hemisphere. If the current becomes to be steady, the geostrophic equiribrium may be established.

Assuming that the quasi-equiribrium is set up the author has calculated in the following manner a difference of geopotential height between two anchored stations. At first, 50 m depth has been taken as reference level. If any depth below 50 m was taken as reference level, the geopotential difference should remain almost constant, because the attributions from the specific volume anomaly in the water layer below 50 m depth are generally small in Lake Biwa-ko, although the temperature is not homogeneous in that layer. In Fig. 4 the geopotential anomaly at some levels referred to 50 m depth is illustrated.

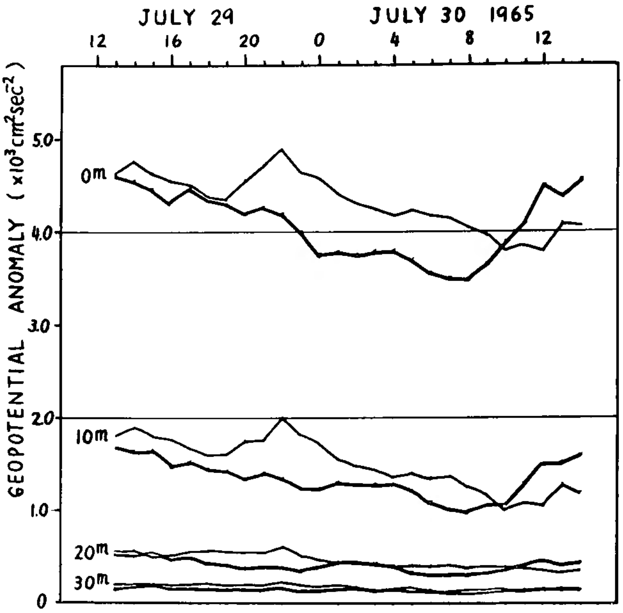

Fig. 4. Time variations of geopotential anomaly at some depths referred to 50 m. Thick line : Station 1. Thin line: Station 2.

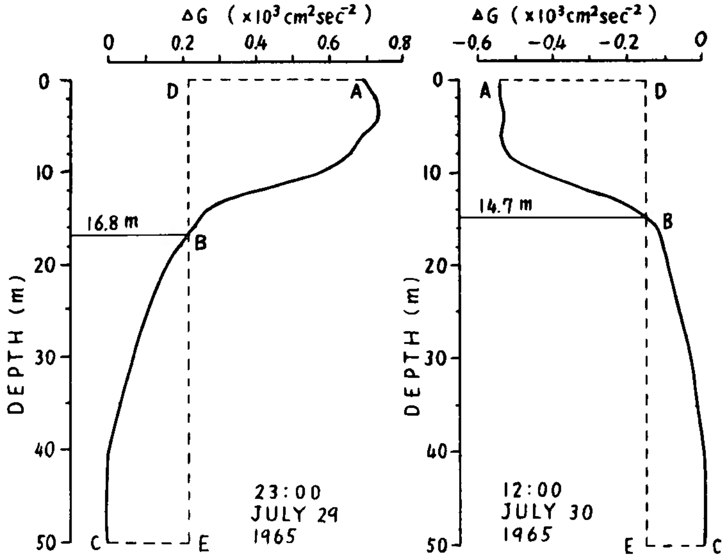

Fig. 5. Examples for the difference profile of the geopotential height between the two anchored stations. Procedure for the determination of no-flow depth is illustrated.

In the northern hemisphere, if the reference depth can be regarded no-flow level, the water current takes such a direction that the station which has larger amount of anomaly is always at right hand side, facing to flowing off. Therefore, Fig. 4 represents that if there was no flow at 50 m depth the water in all the layers above it might flow northwards till morning on 30 th, because the anomaly is larger at Station 2 than at Station 1. But, taking account for the transition of the lake level with the lapse of time at level gauge stations (Fig. 3 B), it cannot happen that the water flows northwards in *all* layers. (The descending trend of the lake levels at all stations illustrated in Fig. 3 B has a correspondence with the outflow from the lake through the Seta River.)

In the next place, therefore, no-flow depth must be selected in such a manner that net water transport through that transverse section corresponds to the outflow of the lake water. The procedure is shown in Fig. 5, where $\Delta G = \Delta G_2 - \Delta G_1$, ΔG_1 and ΔG_2 are geopotential anomalies at Stations 1 and 2 respectively. Transport rate through a section from depth d_1 to depth d_2 is given as

$$\frac{1}{2\omega \sin \varphi} \int_{d_1}^{d_2} \Delta G \, dz,$$

where z is vertical coordinate, ω is angular velocity of the earth's rotation and φ ($=35^\circ\ 15'$ N) is latitude. As flow rate is proportional to area *ABD* or *BCE*, if these areas are equalized, transports towards north and south are balanced. Fig. 5 shows that at 23 h on 29 th the water above 16.8 m depth flows northwards, and below that depth southwards. Similarly at 12 h on 30 th the water above 14.7 m depth flows southwards and below that depth northwards. In the former case northward transport rate is $6.0\times10^3\ m^3/sec$, and southward one is equivalent. In the latter case it is $4.8\times10^3\ m^3/sec$. As discharge of water through the Seta River from the lake amounts to $0.5\times10^3\ m^3/sec$ (from Hydrographic Table, Ministry of Construction) during the observation days, it may be neglected. Determining the no-flow depth in such a method as mentioned above, one can readily infer that from the beginning to 10 h on 30 th the upper layers flow northwards while the lower layers southwards, and that in the subsequent duration the upper layers flow southwards while the lower layers northwards.

Now, it is seen from Fig. 4 that the geopotential anomalies involve those attributed to the transverse internal seiche. In order to eliminate them, therefore, the operation of 9 hours running mean has been adopted at all depths. As a result, no-flow depth is found to lie between 12 m and 18 m during the period under consideration. Total transport northwards of the upper layer is estimated to amount to $2.8\times10^8\ m^3$ and the corresponding volume of the lower layer southwards up to 10 h on 30 th.

The deduced movement of the water described above can be checked in the following way. The event which implies the northward flow of the upper layer coupled with the southward flow of the lower layer will cause to raise the thermocline at both stations. In fact it was raised by 1.2 m at Station 1 and 2.0 m at Station 2 in 14 hours. As the southern area from that section is 1.6×10^2 km^2, if the upward displacement of the thermocline in that area is averaged 2.0 m, total northward flow of the upper layer or southward flow of the lower layer must be 3.2×10^8 m^3. This value does fairly agree with 2.8×10^8 m^3 estimated from the geopotential height difference. Moreover, at about 10 h on 30 th the temperature turned to ascend at both stations (Fig. 2), while the difference of geopotential height between two stations changed a sign at the same time (Fig. 4). These events may support the interpretation mentioned above.

Reversal of water current which occurred at 10 h on 30 th is accounted for the alteration of the wind field which took place in the early morning on that day all over the lake (Fig. 3A). When the wind stress is removed or altered, the water starts into a new equiribrium.

This paper presents that when we determine the stationary pattern of the water circulation which seems to consist of a few gyres, by the method of dynamical calculation in Lake Biwa-ko, the influence of the internal seiche upon the density distribution has to be considered. It must be also given attention to that the stationary pattern may be sometimes modified by the flow caused from the temporary wind field and from the internal seiche.

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